

XAFS spectroscopy. I. Extracting the fine structure from the absorption spectra

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Three independent techniques are used to separate fine structure from the absorption spectra, the background function in which is approximated by

- (i) smoothing spline. We propose a new reliable criterion for determination of smoothing parameter and the method for raising of stability with respect to k_{\min} variation;
- (ii) interpolation spline with the varied knots;
- (iii) the line obtained from bayesian smoothing. This methods considers various prior information and includes a natural way to determine the errors of XAFS extraction.

Particular attention has been given to the estimation of uncertainties in XAFS data. Experimental noise is shown to be essentially smaller than the errors of the background approximation, and it is the latter that determines the variances of structural parameters in subsequent fitting.

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I. INTRODUCTION

X-ray-absorption fine-structure (XAFS), χ , is determined by [1]:

$$\chi(E) = [\mu(E) - \mu_0(E)] / [\mu_0(E) - \mu_b(E)], \quad (1)$$

where μ is the measured absorption, μ_0 is the “atomic” absorption due to electrons of considered atomic level, μ_b is the absorption of other processes. Since the electronic state of an embedded atom is, in general, different from its state in gaseous phase, μ_0 is not the same as for isolated atom and cannot be found experimentally. Therefore a demand arises for an artificial construction of μ_0 .

Usually, μ_b is approximated by a Victoreen polynomial $P = aE^{-3} + bE^{-4}$ [1] or by a more general polynomial P , coefficients of which are found by the least squares method from $\mu(E) = P(E)$ at energies lower than the edge.

Further, energy dependence is transformed to the photoelectron wave number dependence: $k = \sqrt{2m_e(E - E_0)}/\hbar$, where E_0 is the energy of the corresponding absorption edge. Usually, to the E_0 the energy at half the step is assigned or the energy of inflection point of $\mu(E)$. In most practical works the deviation of E_0 from true value, ΔE_0 , is one of the fitting parameters.

The most difficult procedure in extracting of XAFS from the measured absorption is the construction of μ_0 since one cannot definitely distinguish the environmental-born part of absorption from the atomic-like one. All methods for determination of the post-edge background are based on the assumption of its smoothness, and the only criterion for its validity is the absence of low-frequency structure in $\chi(k) \cdot k^w$, i. e. the small absolute value of the Fourier transform (FT) $\rho(r)$ at low r . The review of existing post-edge background methods and the propositions of some new is the main purpose of the article.

Special attention must be paid to the estimation of noise and uncertainties in XAFS data. Experimental noise is shown to be essentially smaller than the errors of the background approximation, and it is the latter that determines the variances of structural parameters in subsequent fitting. The corresponding section of the present article is closely related with the next article devoted to the determining the errors of structural parameters [2].

All described in the article methods for background removal, its error estimations, and XAFS-function corrections are realized in the freeware program VIPER [3] which allows one to vary several parameters by hand and watch the results simultaneously.

II. METHODS OF μ_0 CONSTRUCTION

A. Smoothing spline

Owing to fast algorithm and easy program realization, the approximation of μ_0 by the smoothing spline has become widespread. Let $N + 1$ experimental values of μ_i are defined on the mesh E_i . The smoothing spline μ_0 minimizes the functional

$$J(\mu_0, \mu) = \int_{E_{\min}}^{E_{\max}} [\mu_0''(E)]^2 dE + \frac{1}{\alpha} \sum_{i=0}^N (\mu_{0i} - \mu_i)^2. \quad (2)$$

The smoothing parameter (or regularizer) α is the measure of compromise between smoothness of μ_0 and its deviation from μ . At $\alpha = 0$ the smoothing spline exactly coincides with μ , at $\alpha \rightarrow \infty$ it degenerates to $\mu_0 = \text{const}$. Optimal regularizer should lead to μ_0 containing only low-frequency oscillations and, hence, to χ containing only structural oscillations. The formulation of a new criterion for optimal α we shall consider below.

First, we address another problem, the well-known spline instability with respect to the small variations of input parameters: number of nodes, nodal values of the processed function, and limits on integral. In our case the spline is most sensitive to E_{\min} due to fast growth of μ in the edge. To raise the stability the method was put forward in VIPER program which lies in the use of a prior information specifying the shape of $\mu_0(E)$ dependence. It is known in advance that the absorption edge without so-called white line constitutes nearly smooth step; the white line, if presents, is added to the step. Denote this prior function as $p(E)$. Now we will tend the second derivative of the sought $\mu_0(E)$ not to zero (at the specified deviation of μ_0 from μ) but to the second derivative of $p(E)$. The sought $\mu_0(E)$ is now minimizes the functional

$$J^*(\mu_0, \mu) = \int_{E_{\min}}^{E_{\max}} [\mu_0''(E) - p''(E)]^2 dE + \frac{1}{\alpha} \sum_{i=0}^{N+1} [\mu_{0i} - \mu_i]^2. \quad (3)$$

As seen, in fact there is no need to know $p(E)$ itself, its second derivative is sufficient. The explicit presence of $p(E)$ in the following formulas should be taken as a consequence of the technical trick applied: at first $p(E)$ is subtracted from the data, then it is added to the found spline.

Represent the second derivatives in finite-difference approximation, introduce $\tilde{\mu}_{0i} = \mu_{0i} - p_i$, and denote $\Delta_i = E_{i+1} - E_i$:

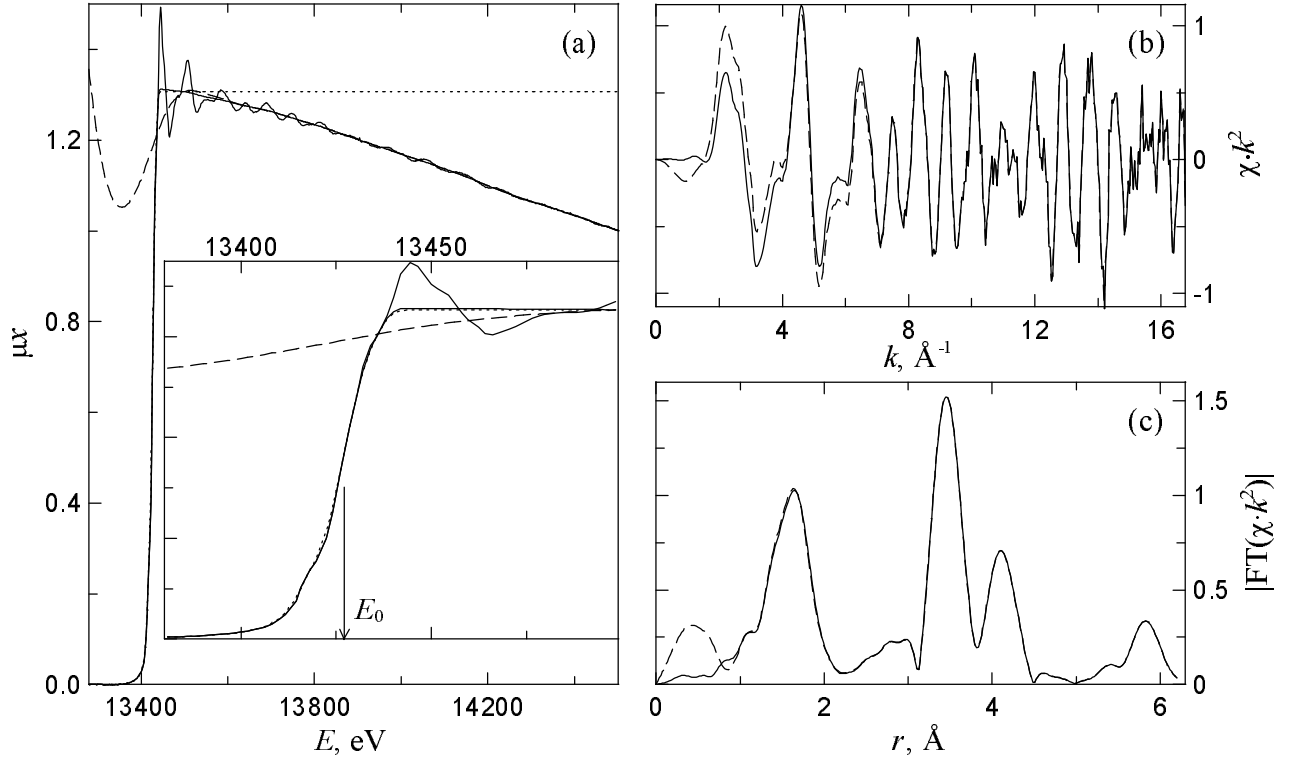


FIG. 1. Extraction of XAFS from the measured absorption using the smoothing spline. Prior function $p(E)$ for the atomic-like absorption is drawn by dots. Solid lines — $\mu_0(E)$, $\chi(k) \cdot k^2$, and $\rho(r)$ obtained with use of the prior function; dashed lines — dittos without prior function. The regularizer α is the same for both cases.

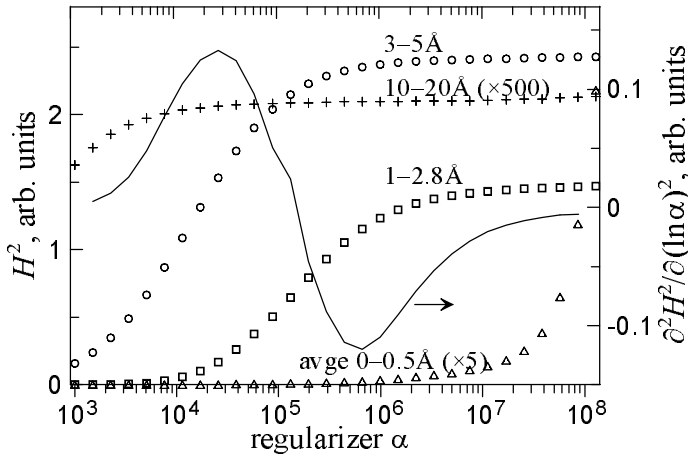


FIG. 2. The $\rho(r)$ peak heights squared, H^2 , maximal in the indicated areas and average over the range $0 < r < 0.5 \text{ \AA}$, as functions of α . To the right axis relates the second derivative of the first peak height squared with respect to $\ln \alpha$.

$$J^*(\mu_0, \mu) = \sum_{i=1}^N [\tilde{\mu}_{0i-1} \Delta_{i-1}^{-1} - \tilde{\mu}_{0i} (\Delta_{i-1}^{-1} + \Delta_i^{-1}) + \tilde{\mu}_{0i+1} \Delta_i^{-1}]^2 + \frac{1}{\alpha} \sum_{i=0}^{N+1} [\tilde{\mu}_{0i} - (\mu_i - p_i)]^2 = J(\tilde{\mu}_0, \mu_i - p_i). \quad (4)$$

Thus, the problem is reduced to the preceding one in which instead of initial data μ_i the difference $\mu_i - p_i$ is appeared. The sought μ_0 is found from the smooth $\tilde{\mu}_0$ as $\mu_{0i} = \tilde{\mu}_{0i} + p_i$. In Fig. 1 is shown an example of the atomic-like absorption approximation by the smoothing spline with and without the use of prior function¹. Energy E_0 was determined at half the step height. Here, we constructed $p(E)$ in the following manner. Found the average value $\bar{\mu}$ of $\mu(E)$ in region $20 \leq E \leq 70 \text{ eV}$ above the absorptance maximum. Moving from the beginning of spectrum, assign $p = \mu$ until $\mu > \bar{\mu}$, further $p = \bar{\mu}$. Then $p(E)$ was smoothed 5 times on 3 points. To perform the Fourier transform, $\chi(k)k^2$ was brought into the uniform scale with $\delta k = 0.03 \text{ \AA}^{-1}$ and multiplied by a Kaiser-Bessel window with parameter $A = 1.5$. As seen, the use of $p(E)$ has led to disappearance of the spurious peak on the absolute value of FT at $r \sim 0.5 \text{ \AA}$.

So far we have considered the atomic-like absorption μ_0 to be a smooth function with no peculiarities. However, in some spectra μ_0 itself has a fine structure [4,5] originating from resonance scattering within absorbing atom or from multi-electron transitions. If in these cases, based on theoretical calculations, experimental information, or empirical considerations, one can nearly indicate the location of peculiarities, their width and weight relatively to the step height, then one would readily construct the prior function $p(E)$ and find the correct μ_0 . Instead of constant value above absorption edge, the prior function would have corresponding valleys and/or peaks.

Let us now define the criterion for determination of smoothing parameter. An attempt to solve the problem was made in Ref. [6], where the requirement was proposed: $H_R - H_N \geq 0.05 H_M$, where H_R is the average value of the weighted Fourier transform magnitude between 0 and 0.25 \AA , H_M is the maximum value in the transform magnitude between 1 and 5 \AA , H_N is the average value of the transform magnitude between 9 and 10 \AA attributed to the noise. Obviously, that this criterion cannot pretend to the generality since depends on the weighting (op. cit., k^3) and the relative contribution of noise and the first coordination shell into spectra.

In the program VIPER we have proposed another approach to the problem based on the consideration of heights of FT peaks as functions of regularizer α (see Fig. 2). On increasing α from zero, μ_0 starts to deviate from the experimental absorption μ , $\rho(r)$ is growing and then saturates, the peaks at larger r being saturated earlier. Clearly, that α should be determined by the first peak height since it is the last to saturate. Define the start of saturation on the minimum of second derivative of the first peak squared with respect to $\ln \alpha$. Declare the value of α in the minimum to be optimal. It is seen that the increase of α from the optimal leads to unwanted rapid growth of ρ at low r .

In the example in Fig. 1 the regularizer is optimized following our new criterion.

¹Here and hereafter for examples is used the spectrum at Bi L_3 absorption edge in $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ at 50 K recorded in transmission mode at D-21 line (XAS-13) of DCI (LURE, Orsay, France) at positron beam energy 1.85 GeV and the average current $\sim 250 \text{ mA}$. Energy step — 1 eV, counting time — 1 s. Energy resolution of the double-crystal Si [311] monochromator (detuned to reject 50% of the incident signal in order to minimise harmonic contamination) with a 0.4 mm slit was about 2–3 eV at 13 keV.

Unfortunately, the method of smoothing spline does not include any approach to the estimations of uncertainties in the μ_0 obtained, in contrast to the following two methods.

B. Interpolation spline drawn through the varied knots

The method was put forward in Ref. [7]. N knots are equally spaced in k space, through them an interpolation spline is drawn. The ordinates of the knots are varied to minimize ρ or $|\rho - \rho_{\text{st}}|$ in the chosen low- r region $0 \leq r \leq r_0$, where ρ_{st} is the absolute value of the FT of a “standard” $\chi_{\text{st}}(k) \cdot k^w$, calculated or experimental. The number of knots must not exceed the value $N_{\text{max}} = 2r_0\Delta k/\pi + 1$, [8] where Δk is the k range of useful data. In the Ref. [7] was asserted that one need to know the “standard” $\chi_{\text{st}}(k) \cdot k^w$ merely approximately since it used only to get an estimate of the leakage from the first shell to the region minimized. The strange thing is that having omitted the question on the accuracy of found knots (as we show below, rather poor), the authors of the cited work made a fine comparison between several theoretical models for $\chi(k)$ calculations.

In Fig. 1 is shown an example of the method application. Ordinates of the 13 knots ($N_{\text{max}} = 13.2$) were varied to minimize the difference $\rho - \rho_{\text{st}}$ at $0 \leq r \leq 1.05 \text{ \AA}$. The function $\chi_{\text{st}}(k)$ was calculated using FEFF6 program [9] (as was pointed above, a crude estimate is sufficient, so details omitted). In the minimized region the $\rho(r)$ is somewhat better than that obtained by the previous method. However, at $k > 15 \text{ \AA}^{-1}$ one can distinguish the obviously wrong behavior of $\chi(k) \cdot k^2$, and the first peak on $\rho(r)$ becomes quite distorted.

Consider now the problem of the accuracy of knot positions y_j , $j = 1, \dots, N$ in fitting $\rho(r)$ to $\rho_{\text{st}}(r)$. As a figure of merit, the χ^2 -statistics appears:

$$\chi^2 = \frac{N_{\text{max}}}{M} \sum_{m=1}^M \frac{[\rho(r_m) - \rho_{\text{st}}(r_m)]^2}{\sigma_m^2}, \quad (5)$$

where σ_m are the errors of $\rho(r_m)$. It can be shown (detailed analysis see in the next article [2]) that under the

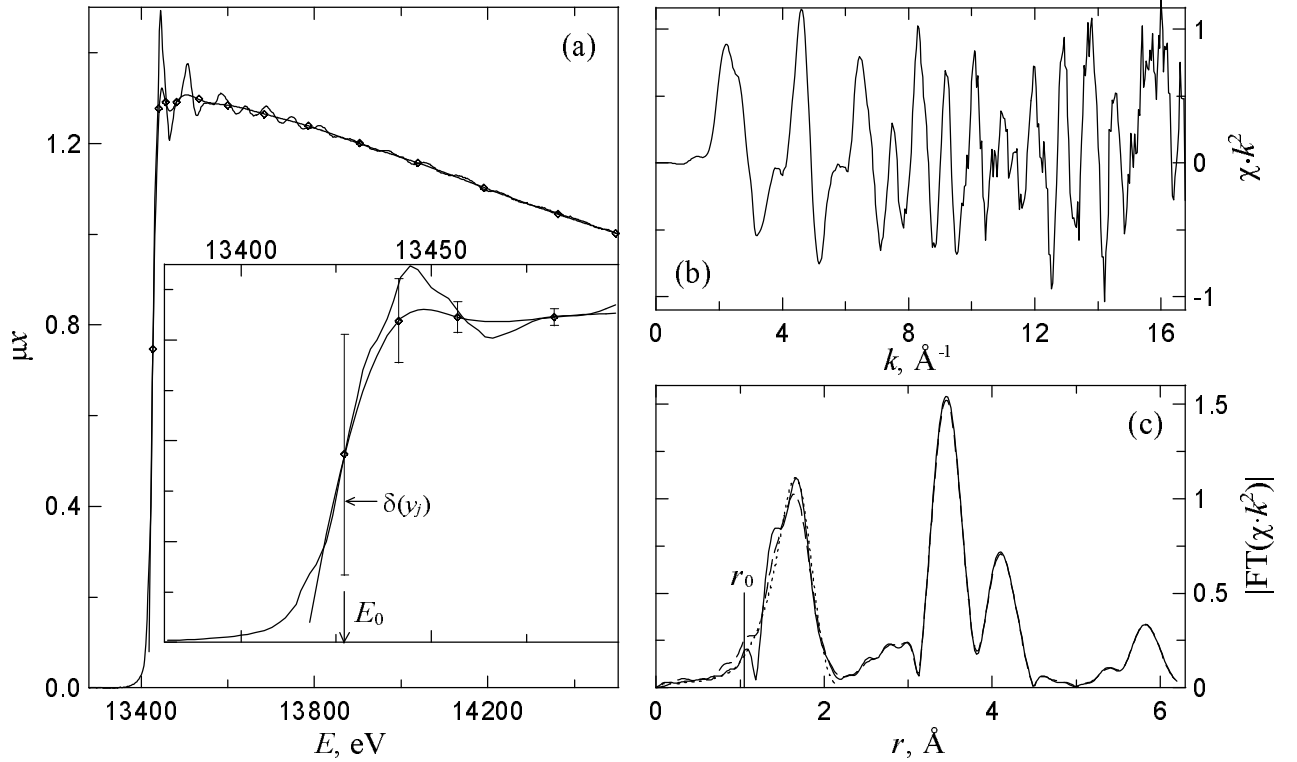


FIG. 3. Extraction of XAFS from the measured absorption using the interpolation spline through the knots with varied ordinates. On (c) the Fourier transforms are shown for sought $\chi(k) \cdot k^2$ (solid), “standard” (dots), and obtained by the previous method (dashed).

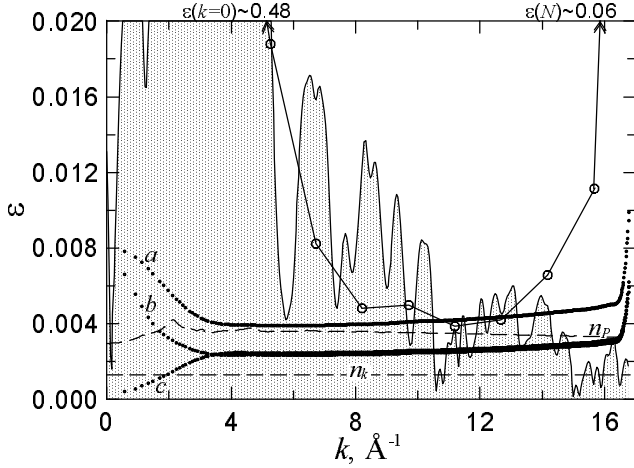


FIG. 4. Errors of $\chi(k)$ extraction. Solid line with open circles — by the method of interpolation spline drawn through the varied knots. Dots — by the method of bayesian smoothing without (a) and with (b c) prior information specifying the second derivative. Besides, (c) uses additional information that $\mu_0(E)$ passes through a point immediately before E_0 . Solid line with filling — the envelope of $\chi(k)$ (not weighted). Dashed lines — the noise estimates from FT (n_k) and from Poisson counting statistics (n_P) (see Sec. III).

assumption of uncorrelated knot positions, the mean-square deviation of y_j from the obtained through the fit optimal value \hat{y}_j equals $\delta(y_j) = (\frac{1}{2}\partial^2\chi^2/\partial y_j^2)^{-1/2}$, where the partial derivatives are calculated in the fitting procedure at the minimum. σ_m are assumed to be constant and equal to the root-mean-square average of $\rho(r)$ between 15 and 25 Å, where solely the noise is present. The errors $\varepsilon_j = \delta(y_j)/[\mu_0(E_j) - \mu_b(E_j)]$ found under such assumptions are shown in Fig. 4 as open circles with the solid line. Notice, that the assumption that the knot positions are not correlated gives quite optimistic ε_j . Actually, several first knot positions appear to be highly correlated; the proper taking into account of the correlations (here we do not present these calculations) raises ε_j at the least as twice. But even these underestimated ε_j are appreciably larger than those given by the following method.

C. Bayesian smooth curve

Ideologically similar to the smoothing spline method is the method of bayesian smoothing (see Appendix on p. 11) proposed in the program VIPER. This method also finds the regularized function μ_0 , the regularizer α is the measure of compromise between smoothness of μ_0 and its deviation from μ . In comparison with smoothing spline method, this method has some advantages. (i) Various prior information on μ_0 can be considered. (ii) In this method the posterior distributions of all μ_{0j} are sought for. From those distributions one can find not only average values but also any desirable momenta, which appears to be an additional difficulty for other methods. (iii) In the framework of the method it is possible also to deconvolute μ with the monochromator rocking curve. The weakness of the method is its low speed (comparing with method II A, not with II B!). On a modern PC the curve drawn through $N \sim 500$ points is smoothed for a few minutes.

In Fig. 5 the bayesian smoothing was done on the mesh of 536 experimental points above E_0 , without and with the prior function (its construction is described in Sec. II A). Besides, in the last case another information was used: the atomic-like absorption must coincide with the total absorption (minus pre-edge background) at energies $E < E_0$. Therefore, we demanded from the bayesian curve to pass through a point nearest (at left) to E_0 . The values $\bar{\mu}_{0j}$ and $\delta^2(\mu_{0j})$ were found by formulas (A31) and (A33). Since the smoothed values do not lie within the limits of $\pm\delta(\mu_{0j})$ from μ_j , we did not look for the most probable smoothness (see. Appendix), instead we considered the regularizer to be known and equal to the optimal one found in the method II A. The introduction of the prior information has significantly diminished the errors of $\chi(k)$ extraction (see dotted curves in Fig. 4) which were defined as $\varepsilon_j = \delta(\mu_{0j})/(\bar{\mu}_{0j} - \mu_{bj})$. This is quite natural: any decrease of our ignorance about μ_0 should narrow the posterior distribution of μ_{0j} for all j . Of course, this concerns the experimental information as well: errors ε_j are the less the more measured points N the spectrum has. Comparing Fig. 1() and Fig. 5(c), it is seen practically perfect coincidence of the results of bayesian smoothing and smoothing spline. From this one can assume the equality of the errors which both methods give.

Could we take into account possible systematic errors in the framework of the method? Yes, if we have the information on their nature and are able to translate it into the mathematics language; such a translation might be rather non-trivial. In any case, now we have the tool to extract from the prior and experimental information not only the sought values but their errors as well.

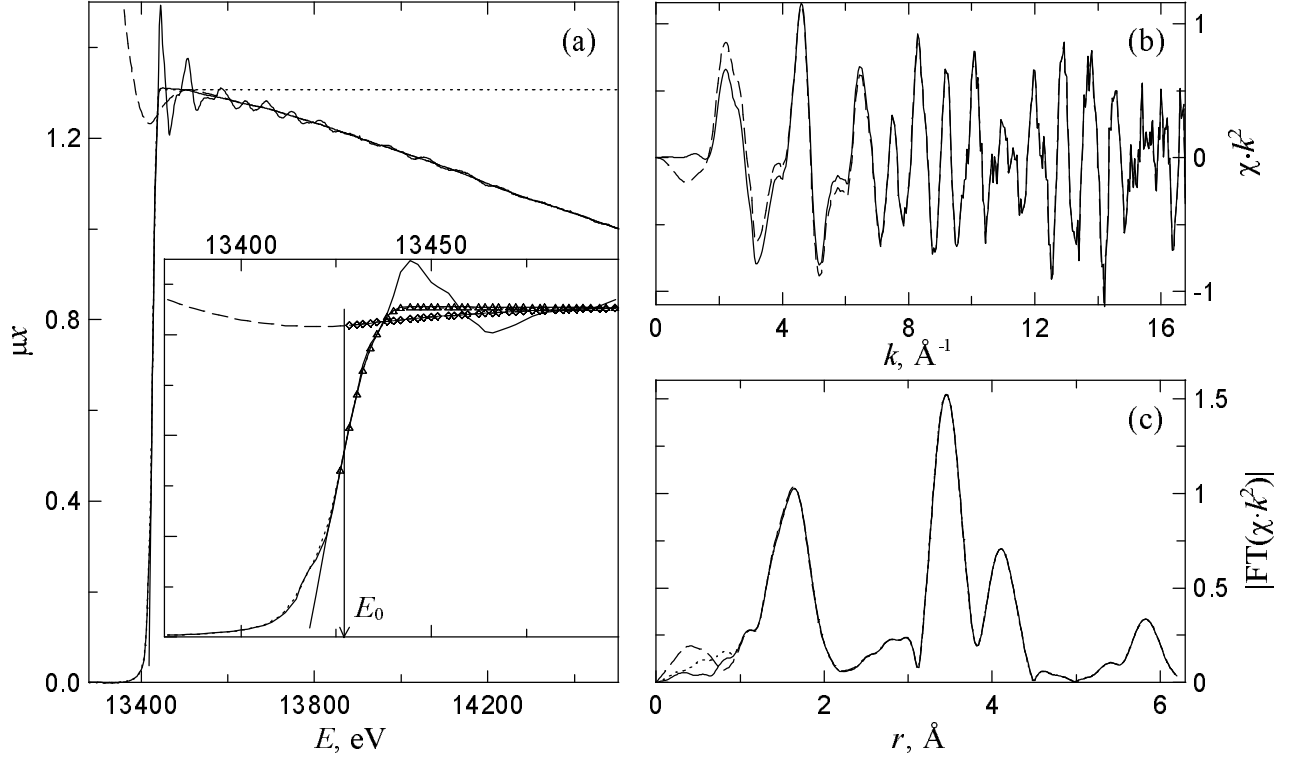


FIG. 5. Extraction of XAFS from the measured absorption using the bayesian smoothing. Prior function $p(E)$ for the atomic-like absorption is drawn by dots. Solid lines — $\mu_0(E)$, $\chi(k) \cdot k^2$, and $\rho(r)$ obtained with the use of the prior function; dashed lines — dittos without prior function. The dot line on (c) is obtained without additional requirement for $\mu_0(E)$ to pass through a point immediately before E_0 . The regularizer α is the same for all cases and equals to the optimal one found for the smoothing spline.

D. Other methods

Consider briefly the methods for μ_0 construction not included into the VIPER program.

A rich variety of computer programs for XAS spectra processing is collected on the International XAFS Society Web-site [10]. The vast majority of them use as an approximation for the atomic-like absorption a smoothing spline or more general piecewise-polynomial representation. For example, in the method of Ref. [11], the construction of μ_0 is divided into several stages: μ_0 is approximated by a low-degree polynomial, obtained $\chi(k)$ is multiplied by k^w , additional μ_0' is drawn again as a low-degree polynomial and subtracted, a smoothing spline then approximates one more additional μ_0'' . The sum of all μ_0 's gives the total atomic-like background. The necessity of the preliminary stages was not discussed op. cit., however, clearly it was caused by the instability of spline with respect to the small variations of input parameters. And the point is not that the preliminary stages make the process stable, but that for each specific spectrum, auxiliary parameters (degrees of polynomials) could provide an acceptable construction of the atomic-like background. Above (in Sec. II A) we proposed the way to rise the stability of spline making the preliminary stages to be redundant.

In Ref. [12] an iterative approach to “atomic background” removal was developed. First a spline is used to obtain a rough estimate of the background; this alone is enough to have a reliable χ at $k > 5 - 6 \text{ \AA}^{-1}$. Over that range the χ obtained is fitted to the theoretical χ_{th} in r -space. The resulting fit parameters are used then to generate $\chi_{\text{th}}(k)$ that extends down to low k . This function is transformed back into e -space and μ_0 is obtained as $\mu_0 = \mu/(\chi_{\text{th}} + 1)$ that need be a little smoothed or fitted by an additional spline. Since the logic of reasoning was inversed: not “find μ_0 to find χ ,” but “find χ to find μ_0 ,” the method is suited for the quest of peculiarities on μ_0 curve, not for structural XAFS-researches. Besides, the range of accuracy of the model appears to be unknown in principle: all, that is not described by the model, is included in μ_0 ; the errors of the background approximation are also undefined.

In the old work [13] for the determination of the background absorption μ_0 was considered the damping of the XAFS amplitude resulting from the measurements with low resolutions (with a large slit width). The superimposition

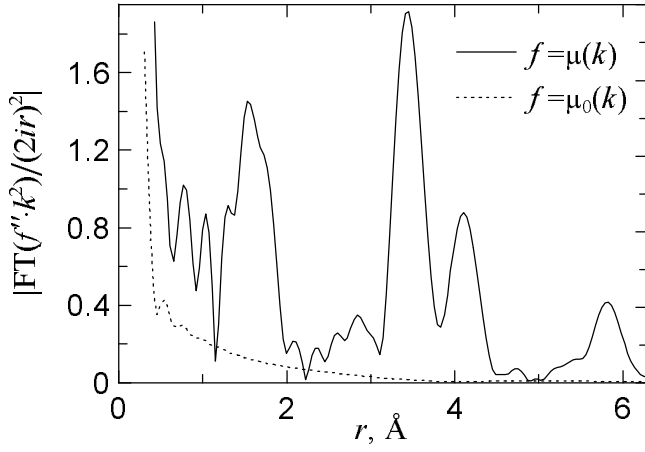


FIG. 6. On the method of Ref. [15]. Solid curve is the FT of “unnormalized $\chi(k) \cdot k^2$ ”, dotted curve is the contribution from the atomic-like absorption.

of two spectra measured with different energy resolutions gives the intersection points, the part of which belong to the μ_0 . Then through the obtained nodal points a smoothing spline is drawn. As the authors of Ref. [13] noted, the measurements of the spectra with worsened resolution are not necessary; the spectra could be damped by the convolution with a “rocking curve,” approximated by a Gaussian function. Of course, the method is correctly works only with a small variation of the Gaussian curve width since for the large width not only the XAFS amplitude is damped but the very edge is washed out. Because of this only the extended part of a spectrum could be reliably determined.

The damping of the XAFS amplitude can be due to other reasons. For instance, as was pointed in Ref. [13], the nodal points may be obtained from the variable-temperature study. This idea was realized in Ref. [14] and is more sound since the atomic-like background is really independent of temperature and with temperature the XAFS amplitude is changed, not the shape of the edge. But for all that it is important that the phase difference between XAFS of different temperatures was negligible, which is true only for low wave numbers. Unfortunately, the method is suitable only for some particular cases (to say nothing of need for measured temperature series of spectra). Op. cit. it was demonstrated for the x-ray-absorption data for the L_3 edge of solid Pb. In those spectra the first crossing of μ and μ_0 occurs already at ~ 15 eV above edge. In our sample spectra the first crossing occurs only at ~ 30 eV, which allows one to find at most 2–3 points and the first of them being situated at $k \gtrsim 2.5 \text{ \AA}^{-1}$.

An interesting approach to the problem of μ_0 determination was reported in Ref. [15]. It is based on the simple identity that relates the FT of some function with the FT of its n -th derivative:

$$\text{FT}[f^{(n)}(k)] = (2ir)^n \text{FT}[f(k)], \quad (6)$$

where the conjugate variables are k and $2r$. Since the atomic-like background is smooth enough, the higher derivatives $\mu^{(n)}(k)$ ($n \geq 2$) are oscillatory near zero. Performing the FT of $\mu^{(n)}(k) \cdot k^w$ and using Eq. (6), one obtains the FT of unnormalized would-be $\chi(k) \cdot k^w$ (see Fig. 6). Op. cit. the low- r part (which in our example is $0 \leq r \lesssim 1.1$) was cut off, and then the back FT was done. As a result, one has the unnormalized $\chi(k) \cdot k^w$ and, having subtracted it from the $\mu(k)$, the atomic-like background on which some peculiarities due to multi-electron excitations can be distinguished. Like the method of Ref. [12], this method is suited for the quest of peculiarities on the μ_0 curve, not for structural XAFS-researches because of evident distortion of the first peak on the FT by the contribution from the atomic-like background. To illustrate this assertion, in Fig. 6 we show the FT of the second derivative of the $\mu_0(k)$ that was found by the present method. As seen, this contribution is not as small.

If the electronic states of an absorbing atom in gaseous phase and in the compound of interest may be considered as equivalent, μ_0 can be set equal to the measured absorption in gas, as was done in Ref [16] for solid, liquid, and gaseous Kr. Some differences in energy positions and relative weights of double-electron excitation channels were taken into account by a model using simple empirical functions which were transferred then to the spectra of liquid and solid Kr. Notice that the proposed in the present paper prior function for the methods of smoothing spline and bayesian smoothing can include additional items corresponding to the multi-electron contributions.

III. ERRORS IN μ_0 CONSTRUCTING, NOISE, AND CHOICE OF LIMITS k_{\min} k_{\max}

For what we need to know the errors of XAFS-function extraction? First, without knowing of these values one cannot in principle aim at their minimization. Second, they are used in the definition of χ^2 -statistics in the fitting

problems; their underestimation is a source of unjustified optimistic errors of fitting parameters. Third, along with analysis of the noise, the errors of μ_0 construction allow us to choose the limits of reliable EXAFS signal, k_{\min} and k_{\max} .

Unfortunately, the issue of quality of XAFS extraction from the measured absorption has not been addressed properly. We see several reasons for that. On the one hand, not having a correctly developed approach to the estimation of the errors of final results (interatomic distances, Debye-Waller factors etc. found via fitting), the errors of EXAFS extraction are useful. On the other hand, only a few methods include approaches to their estimations.

Easily one can compare the errors of different methods (see Fig. 4) and then choose the most reliable one. The problem of plausible limitations on the absolute value of the errors is more difficult. Define “signal” as the envelope of $\chi(k)$ (solid line with gray filling in Fig. 4). It is quite reasonable to demand that the errors of μ_0 construction were less than XAFS signal. For the method of the interpolation spline drawn through the varied knots to meet this requirement leads to the restriction on the photoelectron wave numbers: $2 \lesssim k \lesssim 14 \text{ \AA}^{-1}$. For the bayesian curve a this range is $0 \leq k \lesssim 14 \text{ \AA}^{-1}$, for the bayesian curves b and c this range is wider: $0 \leq k \lesssim 16 \text{ \AA}^{-1}$.

Another factor that limitates the spectrum length is the presence of noise. To determine the noise is a straightforward task for r -space, where XAFS signals at high r have clearly noise character. By Parseval’s identity the noise in r -space is related with the noise in k -space [17]:

$$\int_{k_{\min}}^{k_{\max}} |n_k k^w|^2 dk = 2 \int_0^{\pi/2dk} |n_r|^2 dr. \quad (7)$$

Substitute the mean value over the range $15 < r < 25 \text{ \AA}$ of the FT magnitude squared for $|n_r|^2$. Then

$$n_k^2 = \langle |n_r|^2 \rangle \frac{\pi}{dk} \frac{2w+1}{k_{\max}^{2w+1} - k_{\min}^{2w+1}}. \quad (8)$$

As seen from the formula, n_k depends on dk , the size of evenly-spaced k -grid. Although above we already have used the Fourier transform, the question of choice of dk was not raised yet. The algorithm of fast FT needs the transformed function to be set on a uniform grid. Having chosen a small dk , we artificially obtain the large number of “experimental” values. Naturally, this trick would not give more information than we have, and the errors n_k must be large at the small dk . In our example the choice of dk (0.03 \AA^{-1}) was based on the equality of numbers of experimental points and the nodes of the grid. The signal-to-noise ratio obtained is greater than unity for all the spectrum (see Fig. 4). There was no doubt in that: the signal is visually distinguished even for the very extended end of the spectrum (see Fig. 1(b) and Fig. 5(b)).

The noise can be estimated based on the bayesian considerations [18]. Let after measurements we have the values of counts from the solid-state or gas-filled detectors and let there is a positive real number λ such that the probability that a single count occurs in the time interval dt is

$$P(1|\lambda) = \lambda dt. \quad (9)$$

It can be shown [19] that merely from this assumption follows that the counts obey the Poisson distribution law:

$$P(N|\lambda, T) = \frac{(\lambda T)^N \exp(-\lambda T)}{N!}, \quad (10)$$

where T is the sampling time. The problem is to find the intensity λ and its variance. Using Bayes theorem and introducing prior probabilities $P(N) = 1/N$ and $P(\lambda) = 1/\lambda$ [20], one obtains:

$$P(\lambda|N, T) = \frac{P(N|\lambda, T)P(\lambda)}{P(N)} = \frac{T(\lambda T)^{N-1} \exp(-\lambda T)}{(N-1)!}, \quad (11)$$

that is after measurement the variate $2T\lambda$ follows the χ^2 -distribution with $2N$ degrees of freedom. It is easy to find that $\bar{\lambda} = N/T$, $\bar{\lambda}^2 = N(N+1)/T^2$, and the variance of intensity is $\delta\lambda = \sqrt{N}/T$.

Denote counts from detectors measuring i_0 and i_1 as I_0 and I_1 . By definition the variate $\xi = \frac{i_0/2I_0}{i_1/2I_1}$ follows Fisher’s F -distribution with $(2I_0, 2I_1)$ degrees of freedom. Its expected value and variance are known: $\bar{\xi} = I_1/(I_1-1)$, $\delta^2\xi = I_1^2(I_0+I_1-1)/((I_1-1)^2(I_1-2)I_0)$, from where we find for the absorption in the fluorescence mode ($\mu x = i_0/i_1$):

$$\overline{i_0/i_1} = \frac{I_0}{I_1-1}, \quad \delta^2(i_0/i_1) = \frac{I_0(I_0+I_1-1)}{(I_1-1)^2(I_1-2)}. \quad (12)$$

Further, the variate $\eta = \frac{1}{2} \ln \xi$ follows z -distribution (Fisher's distribution of variance ratio) with $(2I_0, 2I_1)$ degrees of freedom. Its expected value and variance are known: $\bar{\eta} = 0$, $\delta^2 \eta = \frac{1}{4}(I_1 + I_0)/(I_0 I_1)$, from where we find for the absorption in the transmission mode ($\mu x = \ln(i_0/i_1)$):

$$\overline{\ln(i_0/i_1)} = \ln \frac{I_0}{I_1}, \quad \delta^2 \ln(i_0/i_1) = \frac{1}{I_0} + \frac{1}{I_1}. \quad (13)$$

The noise of XAFS-function is

$$n_P = \frac{\delta \mu}{\mu_0 - \mu_b} = \left(\frac{1}{I_0} + \frac{1}{I_1} \right)^{1/2} \frac{1}{\mu_0 - \mu_b}. \quad (14)$$

In our example this noise at $k \gtrsim 15 \text{ \AA}^{-1}$ becomes greater than signal (see Fig. 4). What is the reason for such significant difference between the really present noise n_k and its statistical estimate n_P ? Of course, the reason is in the false premise (9). In practice this condition is realized as: $P(c|\lambda) = \lambda dt$. For example, the photocurrent in an ion-chamber depends on gas pressure, potential applied etc.; these dependencies are contained in c . In other words, the amplification path works in such a way that one photon gives birth to c counts. There is no difficulty in writing the posterior distribution for the generalized premise:

$$P(\lambda|N, T) = \frac{T(\lambda T)^{\frac{N}{c}-1} \exp(-\lambda T)}{\Gamma(N/c)}, \quad (15)$$

with $\bar{\lambda} = N/(cT)$ and $\delta \lambda = \sqrt{N/c}/T$. Thus, having unknown c (and implicitly assigning $c = 1$), we got wrong variances for i_0/i_1 and $\ln(i_0/i_1)$. Unfortunately, in the most of real experiments the association between the probability of a single count event and the radiation intensity (via c) is unknown. In spite of this, the Poisson counting statistics is traditionally used for a long time. For example, in Ref. [21] signal-to-noise ratios are evaluated (assuming $c = 1$) for the different detection schemes.

Practically all programs for XAFS spectra processing [10] to estimate the noise use the Fourier analysis. But then it is the noise that they use as uncertainties ε_i of $\chi(k)$ determination in definition of χ^2 -statistics:

$$\chi^2 = \frac{N_{\max}}{M} \sum_{i=1}^M \frac{[(\chi_{\text{exp}})_i - (\chi_{\text{mod}})_i]^2}{\varepsilon_i^2}. \quad (16)$$

It would be more correct to consider as ε_i the *larger* from the two: the noise and the errors of the construction of μ_0 . In our case (and as a rule) the latter are essentially greater (especially in the method IIB) than the noise. In the following paper [2] we shall show how the understated ε_i lead to optimistic errors of structural parameters.

IV. XAFS-FUNCTION CORRECTION

Because of one reason or another the experimental XAFS might be distorted. Consider some of them.

(i) Let the counts (I) from detectors are associated with the intensities (i) as $i_0 = \varkappa_0 I_0$ and $i_1 = \varkappa_1 I_1$. Then the absorption (in the transmission mode) equals:

$$\mu x = \ln(i_0/i_1) = \ln(I_0/I_1) + \ln(\varkappa_0/\varkappa_1). \quad (17)$$

The second term is a slightly varied function of energy and can be taken into account in independent experiments. Such a distortion appears, for instance, if the absorptance of the gas in ion-chamber detectors depends on energy.

(ii) If some part of incident radiation is not attenuated in the sample as much as expected (due to the pinholes in the sample, harmonics in the incoming beam etc.), that is $i_0 = \varkappa_0 I_0 + b$, then the real absorption is connected with the measured I_0 and I_1 in a complicated way. In Ref. [22] the possible decrease of XAFS amplitude shown to be essential even at low $b/(\varkappa_0 I_0)$ but thick samples. At known ratio $b/(\varkappa_0 I_0)$, the correcting factor can be easily obtained.

(iii) In the fluorescence mode, due to absorptance of the fluorescent signal in the sample itself XAFS spectra strongly depend on the detection geometry. In Ref. [23] the correcting functions are found explicitly.

(iv) The problem of glitches is widespread in the XAFS analysis. The glitches are due to multiple Bragg reflection being satisfied simultaneously and for each given monochromator are manifested in the strictly determined spectral positions. In most cases the glitches seen on curves $I_0(E)$ and $I_1(E)$, vanish on I_0/I_1 ratio. If not, one can easily

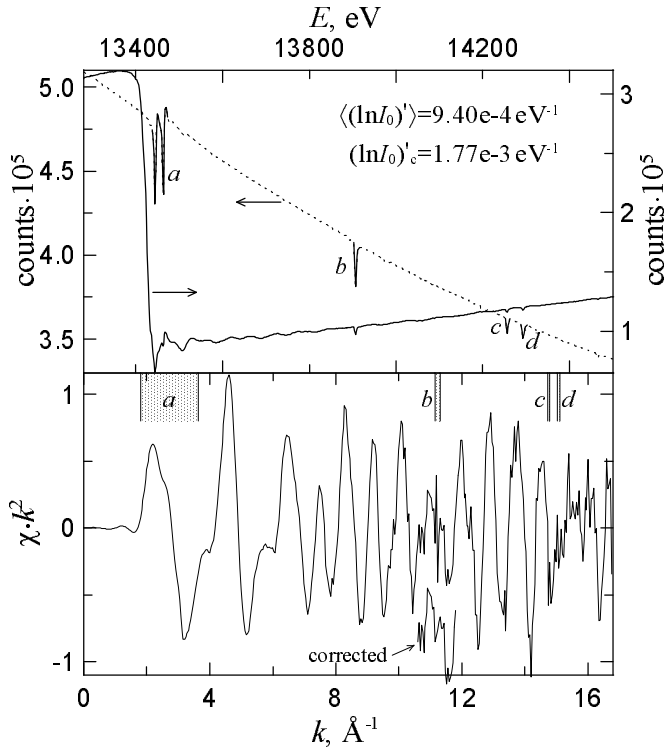


FIG. 7. Energy dependence of experimental counts from ion-chambers. Curve $I_0(E)$ relates to the left axis, $I_1(E)$ — to the right one. In glitch areas the absolute value of the derivative is greater than the critical level specified. On $\chi(k) \cdot k^2$ only the glitch b is manifested. The displaced fragment is $\chi(k) \cdot k^2$ after correction.

get rid of them. For instance, the glitch area, usually extremely thin, is smoothed or, with fixed ends, replaced by a straight-line segment. The main thing in the correct analysis of glitches is their detection.

To detect a glitch on curves μ or χk^w is practically impossible. For this, one needs the primary data $I_0(E)$ and $I_1(E)$, not $\ln(I_0/I_1)$ nor I_0/I_1 . Out of glitches the intensity of incident radiation smoothly, ignoring the noise, depends on energy (see Fig. 7). The idea of detection of glitches via critical level for the derivative $|d \ln I_0 / dE|_c$ is self-evident. For the presented in Fig. 7 $I_0(E)$ curve the absolute value of the derivative in the glitch areas is greater than the critical value chosen to be equal to $1.77 \cdot 10^{-3} \text{ eV}^{-1}$. Having extracted the XAFS, one can see that the first (paired) glitch a is not manifested on $\chi(k) \cdot k^2$, the last two (c d) are obscured by the noise, solely glitch b is clearly pronounced. Now, being in the firm belief that this is not a part of the XAFS, one can eliminate the glitch with ease. Here, we fixed its ends on $\mu(E)$, replaced it by the straight-line segment, and constructed $\chi(k) \cdot k^2$ again.

V. CONCLUSION

In this paper we have considered all stages of XAFS function extraction from the measured absorption. We focused our attention on the most important stage, construction of the atomic-like absorption μ_0 .

For the wide-spread method of approximation of μ_0 by a smoothing spline we have proposed the way to raise the stability by including the prior information about absorption edge shape (“nearly step” or “nearly step with a white line”). Besides we have proposed a new reliable criterion for determination of the smoothing regularizer.

A new method for approximation of μ_0 is proposed, the method of bayesian smoothing. It can include various prior information, which raises the accuracy of XAFS determination. Following this method one finds the distributions of μ_0 in each experimental point, from which one can find not only average values but also any desirable momenta, which appears to be an additional difficulty for other methods. This method was shown to give more accurate atomic-like background than that obtained by the method of Ref [7].

Particular attention has been given to the analysis of noise. We have discussed the difficulties of its estimates on the basis of statistical approach. More reliable is the determination of noise from the Fourier transform. We have shown that the experimental noise is essentially less than the errors of μ_0 construction, and the use of values of noise in the χ^2 -statistics definition appears to be erroneous since leads to the unjustified optimistic errors of structural parameters inferred in fitting procedures. For detailed consideration of the accuracy of fitting parameters see the following paper [2].

APPENDIX: BAYESIAN SMOOTHING AND DECONVOLUTION

1. Posterior distribution for smoothed data

Consider general linear problem of data smoothing with the use of statistical methods (for introduction see review by Turchin *et al.* [24] and the articles from Web-site `bayes.wustl.edu`). Let data \mathbf{d} are defined on the mesh x_1, \dots, x_N and consist of the true values \mathbf{t} and the additive noise \mathbf{n} :

$$d_i = t_i + n_i, \quad i = 1, \dots, N. \quad (\text{A1})$$

The problem of smoothing is to find the best estimates of \mathbf{t} . For an arbitrary node j , find the probability density function for t_j given the data \mathbf{d} :

$$P(t_j|\mathbf{d}) = \int \cdots dt_{i \neq j} \cdots P(\mathbf{t}|\mathbf{d}), \quad (\text{A2})$$

where $P(\mathbf{t}|\mathbf{d})$ is the joint probability density function for all values \mathbf{t} , and the integration is done over all $t_{i \neq j}$. According to Bayes theorem,

$$P(\mathbf{t}|\mathbf{d}) = \frac{P(\mathbf{d}|\mathbf{t})P(\mathbf{t})}{P(\mathbf{d})}, \quad (\text{A3})$$

$P(\mathbf{t})$ being the joint prior probability for all t_i , $P(\mathbf{d})$ is a normalization constant. Assuming that the values n_i are independent in different nodes and normally distributed with zero expected values, the probability $P(\mathbf{d}|\mathbf{t})$, so-called likelihood function, is given by

$$P(\mathbf{d}|\mathbf{t}, \sigma) = (2\pi\sigma^2)^{-N/2} \exp\left(-\frac{1}{2\sigma^2} \sum_{k=1}^N (d_k - t_k)^2\right), \quad (\text{A4})$$

where the standard deviation of the noise, σ , appears as a known value. Later, we apply the rules of probability theory to remove σ from the problem.

Now define prior probability $P(\mathbf{t})$. Let we know in advance that the function $t(x)$ is smooth enough. To specify this information, introduce the norm of the second derivative and indicate its expected approximate value:

$$\Omega(t(x)) = \int \left(\frac{d^2 t}{dx^2}\right)^2 dx \approx \omega. \quad (\text{A5})$$

Denote $\Delta_i = x_{i+1} - x_i$, $i = 1, \dots, N-1$ and represent the second derivative in the finit-difference form:

$$\Omega(t(x)) \equiv \Omega(\mathbf{t}) = \sum_{i=2}^{N-1} [t_{i-1}\Delta_{i-1}^{-1} - t_i(\Delta_{i-1}^{-1} + \Delta_i^{-1}) + t_{i+1}\Delta_i^{-1}]^2 \equiv \sum_{k,l=1}^N \Omega_{kl} t_k t_l. \quad (\text{A6})$$

Ω_{kl} is a five-diagonal symmetric matrix with the following non-zero elements:

$$\begin{aligned} \Omega_{11} &= \Delta_1^{-1}\Delta_2^{-2}, \quad \Omega_{22} = \Delta_2^{-1}(\Delta_1^{-1} + \Delta_2^{-1})^2 + \Delta_2^{-2}\Delta_3^{-1}, \quad \Omega_{12} = -(\Delta_1\Delta_2)^{-1}(\Delta_1^{-1} + \Delta_2^{-1}), \\ &\dots\dots\dots \\ \Omega_{ii} &= \Delta_i^{-1}(\Delta_i^{-1} + \Delta_{i-1}^{-1})^2 + \Delta_i^{-2}\Delta_{i+1}^{-1} + \Delta_{i-1}^{-3}, \\ \Omega_{i-1,i} &= -\Delta_{i-1}^{-2}(\Delta_{i-1}^{-1} + \Delta_i^{-1}) - (\Delta_{i-1}\Delta_i)^{-1}(\Delta_{i-1}^{-1} + \Delta_i^{-1}), \\ \Omega_{i-2,i} &= \Delta_{i-2}^{-1}\Delta_{i-1}^{-2}, \\ &\dots\dots\dots \\ \Omega_{NN} &= \Delta_{N-1}^{-3}, \quad \Omega_{N-1,N-1} = \Delta_{N-1}^{-1}(\Delta_{N-1}^{-1} + \Delta_{N-2}^{-1})^2 + \Delta_{N-2}^{-3}, \quad \Omega_{N-1,N} = -\Delta_{N-1}^{-2}(\Delta_{N-1}^{-1} + \Delta_{N-2}^{-1}). \end{aligned} \quad (\text{A7})$$

In order to introduce the minimum information in addition to that contained in (A6), from all normalized to unity functions $P(\mathbf{t})$ which satisfy the condition (A6) we choose a single one that contains minimum information about \mathbf{t} that is minimizes the functional

$$I[P(\mathbf{t})] = \int P(\mathbf{t}) \ln P(\mathbf{t}) d\mathbf{t} + \beta \left[1 - \int P(\mathbf{t}) d\mathbf{t} \right] + \gamma \left[\omega - \int \Omega(\mathbf{t}) P(\mathbf{t}) d\mathbf{t} \right], \quad (\text{A8})$$

where β and γ are the Larrange multipliers. In minimizing $I[P(\mathbf{t})]$, one obtains the equation set

$$\begin{aligned} \ln P(\mathbf{t}) + 1 - \beta - \gamma \Omega(\mathbf{t}) &= 0 \\ \int P(\mathbf{t}) d\mathbf{t} &= 1 \\ \int \Omega(\mathbf{t}) P(\mathbf{t}) d\mathbf{t} &= \omega, \end{aligned} \quad (\text{A9})$$

that has a solution:

$$P(\mathbf{t}) = (\lambda_1 \cdots \lambda_N)^{-1/2} \left(\frac{2\pi\sigma^2}{\alpha} \right)^{-N/2} \exp\left(-\frac{\alpha}{2\sigma^2} \Omega(\mathbf{t}) \right), \quad (\text{A10})$$

where $\alpha/2\sigma^2 = \gamma = N/2\omega$, and $\lambda_1, \dots, \lambda_N$ are the eigenvalues of the matrix Ω_{kl} . The regularizer α will be used to control the smoothness of \mathbf{t} . The prior distribution obtained is a “soft” one, that is does not demand from the solution to have a strictly prescribed form.

Thus, we have for the probability density function:

$$\begin{aligned} P(t_j | \mathbf{d}, \sigma, \alpha) &\propto \int \cdots dt_{i \neq j} \cdots \sigma^{-2N} \alpha^{N/2} \exp\left(-\frac{\alpha}{2\sigma^2} \sum_{k,l=1}^N \Omega_{kl} t_k t_l \right) \exp\left(-\frac{1}{2\sigma^2} \sum_{k=1}^N (d_k - t_k)^2 \right) \\ &= \int \cdots dt_{i \neq j} \cdots \sigma^{-2N} \alpha^{N/2} \exp\left(-\frac{1}{2\sigma^2} \left[\mathbf{d}^2 - 2 \sum_{k=1}^N d_k t_k + \sum_{k,l=1}^N g_{kl} t_k t_l \right] \right), \end{aligned} \quad (\text{A11})$$

where

$$g_{kl} = \alpha \Omega_{kl} + \delta_{kl}, \quad \mathbf{d}^2 = \sum_{k=1}^N d_k^2. \quad (\text{A12})$$

Since there is no integral over t_j , separate it from the other integration variables:

$$\begin{aligned} P(t_j | \mathbf{d}, \sigma, \alpha) &\propto \sigma^{-2N} \alpha^{N/2} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - 2d_j t_j + g_{jj} t_j^2] \right) \\ &\times \int \cdots dt_{i \neq j} \cdots \exp\left(-\frac{1}{2\sigma^2} \left[\sum_{k,l=1}^N g_{kl} t_k t_l - 2 \sum_{k=1}^N [d_k - g_{kj} t_j] t_k \right] \right), \end{aligned} \quad (\text{A13})$$

Here, the symbol j near the summation signs denotes the absence of j -th item. Further, find the eigenvalues λ'_i and corresponding eigenvectors \mathbf{e}_i of the matrix g_{kl} in which the j -th row and column are deleted, and change the variables:

$$b_i = \sqrt{\lambda'_i} \sum_{k=1}^N t_k e_{ik}, \quad t_k = \sum_{i=1}^N \frac{b_i e_{ik}}{\sqrt{\lambda'_i}} \quad (i, k \neq j). \quad (\text{A14})$$

Using the properties of eigenvectors:

$$\sum_{k=1}^N g_{lk} e_{ik} = \lambda'_i e_{il}, \quad \sum_{k=1}^N e_{lk} e_{ik} = \delta_{li} \quad (l, i \neq j), \quad (\text{A15})$$

one obtains:

$$\begin{aligned} P(t_j | \mathbf{d}, \sigma, \alpha) &\propto \sigma^{-2N} \alpha^{N/2} \exp\left(-\frac{1}{2\sigma^2} [(\mathbf{d}^2 - \mathbf{h}^2) - 2t_j(d_j - \mathbf{h}\mathbf{u}) + t_j^2(g_{jj} - \mathbf{u}^2)] \right) \\ &\times \int \cdots db_{l \neq j} \cdots \exp\left(-\frac{1}{2\sigma^2} \sum_{i=1}^N [b_i - h_i + u_i t_j]^2 \right), \end{aligned} \quad (\text{A16})$$

where new quantities were introduced:

$$\begin{aligned} h_i &= \frac{1}{\sqrt{\lambda_i}} \sum_{k=1}^N d_k e_{ik}, & u_i &= \frac{1}{\sqrt{\lambda_i}} \sum_{k=1}^N g_{kj} e_{ik}, \\ \mathbf{h}^2 &= \sum_{i=1}^N h_i^2, & \mathbf{u}^2 &= \sum_{i=1}^N u_i^2, & \mathbf{hu} &= \sum_{i=1}^N h_i u_i. \end{aligned} \quad (\text{A17})$$

Evaluating the $N - 1$ integrals in (A16), one finally obtains the posterior probability for j -th node:

$$P(t_j | \mathbf{d}, \sigma, \alpha) \propto \sigma^{-(N+1)} \alpha^{N/2} \exp\left(-\frac{1}{2\sigma^2}[(\mathbf{d}^2 - \mathbf{h}^2) - 2t_j(d_j - \mathbf{hu}) + t_j^2(g_{jj} - \mathbf{u}^2)]\right). \quad (\text{A18})$$

2. Eliminating nuisance parameters

In most real problems σ and α are not known. To eliminate σ is a quite straightforward problem:

$$P(t_j | \mathbf{d}, \alpha) = \int d\sigma P(t_j, \sigma | \mathbf{d}, \alpha) = \int d\sigma P(\sigma) P(t_j | \mathbf{d}, \sigma, \alpha), \quad (\text{A19})$$

one needs only to know a prior probability $P(\sigma)$. Having no specific information about σ , a Jeffreys prior $P(\sigma) = 1/\sigma$ is assigned [20]. Then

$$\begin{aligned} P(t_j | \mathbf{d}, \alpha) &\propto \int_0^\infty d\sigma \sigma^{-(N+2)} \exp\left(-\frac{1}{2\sigma^2}[(\mathbf{d}^2 - \mathbf{h}^2) - 2t_j(d_j - \mathbf{hu}) + t_j^2(g_{jj} - \mathbf{u}^2)]\right) \\ &\propto [(\mathbf{d}^2 - \mathbf{h}^2) - 2t_j(d_j - \mathbf{hu}) + t_j^2(g_{jj} - \mathbf{u}^2)]^{-(N+1)/2}. \end{aligned} \quad (\text{A20})$$

Introducing the substitution

$$w_j^2 = N \frac{(g_{jj} - \mathbf{u}^2)^2}{(\mathbf{d}^2 - \mathbf{h}^2)(g_{jj} - \mathbf{u}^2) - (d_j - \mathbf{hu})^2} \left(t_j - \frac{d_j - \mathbf{hu}}{g_{jj} - \mathbf{u}^2}\right)^2, \quad (\text{A21})$$

one obtains the Student t -distribution with N degrees of freedom:

$$P(w_j | \mathbf{d}, \alpha) \propto \left(1 + \frac{w_j^2}{N}\right)^{-(N+1)/2} \quad (\text{A22})$$

with zero average and the variance $N/(N - 2)$. From where one finds for t_j :

$$\bar{t}_j = \frac{d_j - \mathbf{hu}}{g_{jj} - \mathbf{u}^2}, \quad \delta^2(t_j) = \frac{(\mathbf{d}^2 - \mathbf{h}^2)(g_{jj} - \mathbf{u}^2) - (d_j - \mathbf{hu})^2}{(g_{jj} - \mathbf{u}^2)^2} \frac{1}{N - 2}. \quad (\text{A23})$$

Thus, we have got rid of unknown σ and found the expressions for mean values t_j and their dispersions at known regularizer α . To eliminate the latter is more difficult. The idea is not to find the smoothest solution, but the solution of the most probable smoothness. For that we will find the posterior probability:

$$P(\alpha | \mathbf{d}) = \int d\mathbf{t} d\sigma P(\alpha, \sigma, \mathbf{t} | \mathbf{d}) = \int d\mathbf{t} d\sigma P(\alpha, \sigma) P(\mathbf{t} | \alpha, \sigma, \mathbf{d}). \quad (\text{A24})$$

Assuming that α and σ are independent and using Bayes theorem (A3), one obtains:

$$P(\alpha | \mathbf{d}) \propto \int d\mathbf{t} d\sigma P(\alpha) P(\sigma) P(\mathbf{t} | \alpha, \sigma) P(\mathbf{d} | \mathbf{t}, \alpha, \sigma). \quad (\text{A25})$$

Substituting (A10) for the prior probability $P(\mathbf{t} | \alpha, \sigma)$, (A4) for the likelihood, and a Jeffreys prior $P(\sigma) = 1/\sigma$ and $P(\alpha) = 1/\alpha$, one obtains the posterior distribution for the regularizer α :

$$\begin{aligned}
P(\alpha|\mathbf{d}) &\propto \int d\mathbf{t} d\sigma \sigma^{-2N-1} \alpha^{N/2-1} \exp\left(-\frac{\alpha}{2\sigma^2} \sum_{k,l=1}^N \Omega_{kl} t_k t_l\right) \exp\left(-\frac{1}{2\sigma^2} \sum_{k=1}^N (d_k - t_k)^2\right) \\
&= \int d\mathbf{t} d\sigma \sigma^{-2N-1} \alpha^{N/2-1} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - 2 \sum_{k=1}^N d_k t_k + \sum_{k,l=1}^N g_{kl} t_k t_l]\right),
\end{aligned} \tag{A26}$$

where matrix g_{kl} was defined in (A12). After its diagonalization, analogously to what was done above, finally one obtains:

$$P(\alpha|\mathbf{d}) \propto (\lambda'_1 \cdots \lambda'_N)^{-1/2} \alpha^{N/2-1} [\mathbf{d}^2 - \mathbf{h}^2]^{-N/2}, \tag{A27}$$

where \mathbf{h}^2 is given by

$$\mathbf{h}^2 = \sum_{i=1}^N h_i^2, \quad h_i = \frac{1}{\sqrt{\lambda'_i}} \sum_{k=1}^N d_k e_{ik}, \tag{A28}$$

and λ'_i and \mathbf{e}_i are the eigenvalues and eigenvectors of g_{kl} . Having found the maximum of the posterior probability (A27) or having averaged over it the expression (A23), one has the sought \mathbf{t} with the most probable smoothness. However it is necessary to point out that this procedure narrows the applicability of the bayesian smoothing down to the class of tasks where the smoothed values lie in most within the limits $\pm\sigma$ from the most probable. In practice, there possible other tasks where the condition (A1) is treated more wider and the smoothed values exceed the bounds of noise.

3. Expressions for smoothed values and their variances

The formulas (A23) appear useless in practice since require to find the eigenvalues and eigenvectors for the matrix of rank $N - 1$ on each node. Those formulas have merely a methodological value: the explicit expressions for posterior probabilities enable one to find the average of *arbitrary* function of t_j . However, \bar{t}_j and $\delta^2(t_j)$ could be found significantly easier. Using (A19) and (A11), represent \bar{t}_j as:

$$\begin{aligned}
P(\sigma)P(t_j|\mathbf{d}, \sigma, \alpha)dt_j \\
\propto \int d\mathbf{t} d\sigma \sigma^{-2N-1} t_j \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - 2 \sum_{k=1}^N d_k t_k + \sum_{k,l=1}^N g_{kl} t_k t_l]\right).
\end{aligned} \tag{A29}$$

Performing the diagonalization, one obtains:

$$\begin{aligned}
\bar{t}_j &\propto \int d\mathbf{b} d\sigma \sigma^{-2N-1} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - \mathbf{h}^2]\right) \left(\sum_{i=1}^N \frac{b_i e_{ij}}{\sqrt{\lambda'_i}}\right) \exp\left(-\frac{1}{2\sigma^2} \sum_{i=1}^N [b_i - h_i]^2\right) \\
&\propto \sum_{i=1}^N \frac{h_i e_{ij}}{\sqrt{\lambda'_i}} \int d\sigma \sigma^{-N-1} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - \mathbf{h}^2]\right),
\end{aligned} \tag{A30}$$

from where

$$\bar{t}_j = \sum_{i=1}^N \frac{h_i e_{ij}}{\sqrt{\lambda'_i}}. \tag{A31}$$

Analogously, for the variance $\delta(t_j)$ one has:

$$\begin{aligned}
\delta^2(t_j) &\propto \int d\mathbf{b} d\sigma \sigma^{-2N-1} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - \mathbf{h}^2]\right) \left(\sum_{i=1}^N \frac{(b_i - h_i) e_{ij}}{\sqrt{\lambda'_i}}\right)^2 \exp\left(-\frac{1}{2\sigma^2} \sum_{i=1}^N [b_i - h_i]^2\right) \\
&\propto \sum_{i=1}^N \frac{e_{ij}^2}{\lambda'_i} \int d\sigma \sigma^{-N-1} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - \mathbf{h}^2]\right) \sigma^2.
\end{aligned} \tag{A32}$$

Normalizing, one finally obtains:

$$\begin{aligned}\delta^2(t_j) &= \frac{\int d\sigma \sigma^{-N+1} \exp(-[\mathbf{d}^2 - \mathbf{h}^2]/2\sigma^2)}{\int d\sigma \sigma^{-N-1} \exp(-[\mathbf{d}^2 - \mathbf{h}^2]/2\sigma^2)} \sum_{i=1}^N \frac{e_{ij}^2}{\lambda'_i} \\ &= \frac{\Gamma(\frac{N}{2} - 1)}{([\mathbf{d}^2 - \mathbf{h}^2]/2)^{N/2-1}} \frac{([\mathbf{d}^2 - \mathbf{h}^2]/2)^{N/2}}{\Gamma(\frac{N}{2})} \sum_{i=1}^N \frac{e_{ij}^2}{\lambda'_i} = \frac{[\mathbf{d}^2 - \mathbf{h}^2]}{N-2} \sum_{i=1}^N \frac{e_{ij}^2}{\lambda'_i}.\end{aligned}\quad (\text{A33})$$

Now we got the usable formulas, which require to find the eigenvalues and eigenvectors for the matrix of rank N just *one time*.

4. Addenda to the bayesian smoothing

(i) Let the curvature of the function $t(x)$ is approximately known in advance. To specify this information, introduce the norm of the difference between d^2t/dx^2 and approximately known second derivative d^2f/dx^2 :

$$\Omega(t(x)) = \int \left(\frac{d^2t}{dx^2} - \frac{d^2f}{dx^2} \right)^2 dx \approx \omega. \quad (\text{A34})$$

Notice, that there is no need to know $f(x)$ itself, its second derivative is sufficient. The explicit presence of $f(x)$ in the following formulas should be taken as a consequence of the technical trick applied: at first $f(x)$ is subtracted from the data, then it is added to the found solution.

Everywhere in formulas (A6–A33) make the substitutions:

$$\tilde{t}_i = t_i - f_i, \quad \tilde{d}_i = d_i - f_i, \quad i = 1, \dots, N. \quad (\text{A35})$$

Performing the described above procedure for smoothing, one finds \tilde{t}_i , from which by inverse transformation the sought vector is given by $\mathbf{t} = \tilde{\mathbf{t}} + \mathbf{f}$.

(ii) In some tasks the value on the starting (zero) node is known without measurement. This sort of prior information represents a “hard” one, that is it restricted the class of possible solutions; in the given case the solution must pass through the known zero node. The quadratic form $\Omega(\mathbf{t})$ (or $\Omega(\tilde{\mathbf{t}})$ in the case of approximately known second derivative) in the expression for the prior probability has changed:

$$\Omega(\mathbf{t}) = \sum_{i=1}^{N-1} [t_{i-1}\Delta_{i-1}^{-1} - t_i(\Delta_{i-1}^{-1} + \Delta_i^{-1}) + t_{i+1}\Delta_i^{-1}]^2 \equiv \sum_{k,l=1}^N \Omega_{kl}t_kt_l + \Omega_{00}t_0^2 + 2\Omega_{01}t_0t_1 + 2\Omega_{02}t_0t_2, \quad (\text{A36})$$

the first few matrix elements of Ω_{kl} now are:

$$\begin{aligned}\Omega_{00} &= \Delta_0^{-2}\Delta_1^{-1}, \quad \Omega_{01} = -(\Delta_0\Delta_1)^{-1}(\Delta_0^{-1} + \Delta_1^{-1}), \quad \Omega_{02} = \Delta_0^{-1}\Delta_1^{-2}, \\ \Omega_{11} &= \Delta_1^{-1}(\Delta_0^{-1} + \Delta_1^{-1})^2 + \Delta_1^{-1}\Delta_2^{-2}, \quad \Omega_{12} = -\Delta_1^{-2}(\Delta_1^{-1} + \Delta_0^{-1}) - (\Delta_1\Delta_2)^{-1}(\Delta_1^{-1} + \Delta_2^{-1}).\end{aligned}\quad (\text{A37})$$

If $t_0 = 0$ (or $\tilde{t}_0 = 0$), none further changes to the formulas of smoothing (A6–A33) are needed; at $t_0 \neq 0$ the changes are evident: instead of the scalar product $\mathbf{d}\mathbf{t}$ in (A11) will be $(\mathbf{d} - \hat{\mathbf{d}})\mathbf{t}$, where $\hat{d}_1 = \alpha t_0 \Omega_{01}$, $\hat{d}_2 = \alpha t_0 \Omega_{02}$, all remaining $\hat{d}_i = 0$; to the \mathbf{d}^2 the term $\alpha t_0^2 \Omega_{00}$ will be added.

(iii) Making some changes in the considered above problem of smoothing allows one to solve the problem of deconvolution. If the experimental value d_j on some node j is determined not only by t_j but also by the values of some neighboring nodes, then instead of (A1) we have:

$$d_i = \sum_{j=1}^N r_{ij}t_j + n_i, \quad i = 1, \dots, N, \quad (\text{A38})$$

where r_{ij} is the grid representation of the impulse response function. Instead of expression (A4), for the likelihood now we have:

$$P(\mathbf{d}|\mathbf{t}, \sigma) = (2\pi\sigma^2)^{-N/2} \exp\left(-\frac{1}{2\sigma^2} \sum_{k=1}^N \left[d_k - \sum_{i=1}^N r_{ik}t_i\right]^2\right), \quad (\text{A39})$$

and instead of (A11), the posterior probability for t_j is now expressed as:

$$P(t_j|\mathbf{d}, \sigma, \alpha) \propto \int \cdots dt_{i \neq j} \cdots \sigma^{-2N} \alpha^{N/2} \exp\left(-\frac{1}{2\sigma^2} [\mathbf{d}^2 - 2 \sum_{k=1}^N D_k t_k + \sum_{k,l=1}^N G_{kl} t_k t_l]\right), \quad (\text{A40})$$

where

$$G_{kl} = \alpha \Omega_{kl} + \sum_{i=1}^N r_{ik} r_{il}, \quad D_k = \sum_{i=1}^N r_{ik} d_i. \quad (\text{A41})$$

Further steps for finding of \mathbf{t} are analogous to the described above.

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